Review Article

Effects of Density Profile on the Mechanical Properties of Particleboard and Fiberboard*[1]

Ee Ding WONG*[2]

(Received May 31, 1999)

Keywords: density profile, mechanical properties, particleboard, fiberboard

Contents

Introduction

In the manufacture of composite boards, with similar input of raw materials, hot pressing method is the most significant factor that influences the final board properties. During hot pressing, the interaction among heat, moisture, and pressure gives rise to non-uniform deformation of the elements, and results in an uneven density distribution along the thickness direction of the board. This density profile typically resembles a "U-shape", with peak density (PD) appearing near the board surfaces, and the lowest density in the core region. Furnish characteristics, e.g., configuration, compressibility, MC and its distribution; and hot pressing conditions, including type, temperature, closing speed, pressure and duration, are among the critical factors affecting the formation of density profile[1–4].

The existence of density profile in particleboards was first realized in 1950's by Kollmann[5], Iwashita *et al.*[6] and Strickler[7]. The presence of this vertical density gradient has been reported to result in higher bending strength, but lower internal bond and interlaminar shear. A steep density gradient in low-density particleboard could cause shear failure to occur before the specimen fails in tension or compression during bending, hence reducing the modulus of rupture (MOR)[8]. So far, most of the reports on the effects of density profile on the bending properties are qualitative in nature, and the wide variations in processing parameters in these different studies make quantitative comparison very difficult, if not impossible.

The aims of this study therefore include:

a) investigation of the effects of selected processing factors on the formation of density profile, and

b) clarification of the specific effects of density profile on the board bending properties through actual experiment and simulation by finite element analysis.

Chapter 1 Definition of Density Profile

The earliest way of determining the density profile along the thickness of composite boards was by gravimetric method[9]. This is followed by the introduction of torsion-shear method[10], x-ray radiography method[11], and scanning gamma densitometer[12]. The latest develop-

---

*[1] This review article is part of the Ph.D. dissertation by the author entitled "Density Profile: Its formation and effects on the properties of particleboard and fiberboard" at Kyoto University, 1999. The study was financially supported by Monbusho, Japan, and Universiti Putra Malaysia, Malaysia.

*[2] Faculty of Forestry, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor D.E., Malaysia.

ments include continuous, in-line, real time measurement and monitoring of density profile on the production line by means of scanning gamma densitometer[13] and scattered radiation of x-ray photos[14].

In this study, density profile was determined by means of gamma radiation transmitted through 50 mm by 50 mm samples along the thickness at intervals of 0.1 mm (Institute of Geological and Nuclear Sciences Ltd., 1994). The density profile was found to be near symmetrical on both sides along the central board thickness, and its definition is illustrated in Fig. 1.1. PD refers to the mean of the highest densities measured within each half of the profile. CD is the average density of the central region situated within 20% of the total board thickness. Pdi denotes the distance of PD from board surface, whereas peak base (Pb) is the distance between the intersections of density profile contour and the line of MD. The profile gradient facing the core is expressed as gradient factor (GF), which is the horizontal distance between the centerline (CL), from the mid-point of vertical distance between PD and CD, to the profile contour. The discrete values of Pdi, GF and Pb are means of data from the 2 symmetrical halves, and are respectively expressed as percentages of the total board thickness. Peak area (PA), estimated as 1/2 Pb (PD-MD), represents the area enclosed by density profile contour above the mean density (MD).

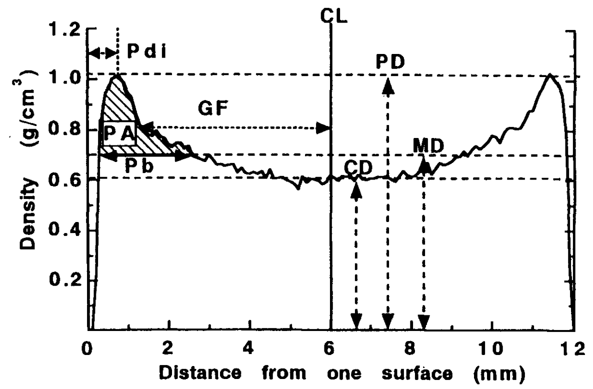

Fig. 1.1. Definition of density profile along the thickness of particleboard and fiberboard MD, mean density; PD, peak density; CD, core density; PA, peak area; CL, center line; GF, gradient factor*; Pdi, peak distance*; Pb, peak base*. * Values expressed as percent of the total board thickness.

Chapter 2 Effects of Density Profile on the Mechanical Properties of Boards

In order to produce a range of particleboards and fiberboards with varied density profiles, processing factors which are known to be among the more influential on density profile formation, namely mat MC level and distribution, and hot pressing method[2,7], i.e., press closing speed and single- or two-step hot pressing, were manipulated.

2.1 Materials and methods

2.1.1 Materials

Lauan (*Shorea* spp.) particles with an air-dried density of 0.4 g/cm^3 were prepared using a knife-ring flaker, and screened to exclude the fines. In order to achieve uniform board properties, only relatively fine and uniform particles were used, i.e., about 80% of 0.13–0.61 mm thickness, 0.3–1.4 mm width and 4–13 mm length. The distribution of the particles based on screening test is as shown in Table 1.

For fiberboard, the lauan fibers were produced by using a double-disc refiner. These fibers were relatively fine, with an average fiber length of about 1 mm. The MC of these particles/fibers were adjusted to 3, 5, 10 or 20% accordingly, by oven-drying at mild temperatures (60 and 40°C for particles and fibers, respectively), or spraying with the necessary amount of water and kept in plastic bags for a week prior to board fabrication.

A polymeric isocyanate resin, UL4811, formulated by Gun-ei Chemical Industries Corp., was used as the binder at a resin content of 8% based on the oven-dried (OD) weight of the particles/fibers. In order to obtain a suitable viscosity for spraying, and to ensure better resin distribution, 20 and 30% of acetone was added as resin diluent based on the weight of isocyanate resin in the fabrication of particleboard and fiberboard, respectively.

2.1.2 Methods

Two types of particleboards and fiberboards were produced, namely, boards with a flat, uniform vertical density distribution along the board thickness, termed as "homo-profile" boards hereafter, and "conventional" boards with U-shaped vertical density profile.

(1) Homo-profile boards

A series of homo-profile particleboard and fiberboard were manufactured to different density levels ranging from 0.3 to 1.1 g/cm^3. The dimensions of the particleboard and fiberboard were 12×300×300 mm and 12×365×385 mm, respectively.

Table 1. Distribution of particle furnish based on mesh analysis.

Mesh No.	$x>4$	$4>x>9$	$9>x>20$	$20>x>32$	$32>x$
Mesh opening (μm)	$x>4{,}760$	$4{,}760>x>2{,}000$	$2{,}000>x>840$	$840>x>500$	$500>x$
Particle geometry (mm)					
Length	—	11–21	5–13	4– 8	—
Width	—	1.4 –2.5	0.6 –1.4	0.3 –0.7	—
Thickness	—	0.26–0.64	0.29–0.61	0.13–0.33	—
Weight (g)	Negligible	3.3	16.9	12.1	4.8
Percentage (%)	Negligible	9	45	33	13

For particleboard, an airless spray gun was used to add resin to the particles being rotated in a blender. A total of six hand-formed mats were pressed simultaneously at ambient temperature to a targeted thickness of 12 mm using distance bars, in a 900×2,000 mm single opening press of 500 ton capacity. The press platens were then heated up to 160°C, in order to achieve complete curing of the resin. The boards were removed from the press immediately when the platens reached 160°C.

For fiberboard, the fiber lumps were segregated into individual fibers by brushing and blowing-up by air in an air-cyclic pipeline blender of about 20 m length[15]. The resin adhesive was then added to the fibers in the pipeline by means of an airless spray gun. Mat forming was done by passing the fibers blended with adhesive through the same pipeline, this time ending in a forming box via a forming roller. The boards were platen pressed in the same way as particleboard. It took 1 h to 1 h 45 min for the platens to reach 160°C.

(2) Conventional boards

Conventional particleboard and fiberboard were fabricated at 0.5 and 0.7 g/cm^3 density levels. The main production factors being manipulated include mat MC level and distribution, press closing speed, and single- or two-step hot pressing. A newly developed press which adjusts the board thickness by displacement control, i.e., raising or lowering of spacers was used. In two step-pressing, the fiber mat was first compressed to a thickness of 10 or 8 mm to obtain highly densified surfaces in the first step. The pressure was then released immediately by raising the spacers to a final thickness of 12 mm. The apparent mat densities were 0.13–0.18 and 0.07–0.13 g/cm^3 for particles and fibers, respectively, and the corresponding maximum specific pressures ranged from 2.9–6.9 and 2.6–5.9 MPa during hot pressing. The dimensions of the particleboard and fiberboard produced were 12×350×400 and 12×365×385 mm, respectively. Tables 2a and 2b summarize the processing parameters for conventional particleboard and fiberboard, respectively.

2.2 Testing and evaluation

For conventional evaluation of mechanical properties, the boards were conditioned for 1 week at 20°C and 65±5% relative humidity (RH). The unsanded boards were then evaluated based on the JIS for Particleboards (JIS A5908, 1994)[16] and Fiberboards (JIS A5905, 1994)[17], accordingly.

Static bending test was conducted on three specimens of 40×200 mm from each board, using a 3-point bending test over an effective span of 180 mm, at a loading speed of 10 mm/min. The MOE of fiberboards was also measured by non-destructive dynamic flexural method, i.e., free-free beam method, where the MOE was calculated based on the resonance frequency of the first mode vibration[18]. The dimensions of the specimens for free-free beam method were the same as those used for the static bending test.

After static bending test, the undamaged parts of the sample were used for screw withdrawal resistance (SWR)

Table 2a. Processing variables for the conventional particleboards.

Code	MC (%)	Particle proportions[1)]	Overall mat MC (%)	Press closing speed (mm/s)[2)]
Uniform mat MC				
5 MC	5	—	5	M
10 MC	10	—	10	S, M, F
20 MC[3)]	20	—	20	M
Distributed mat MC	face/core/face	face/core/face		
MC 18/5-1/4/1	18 : 5 : 18	1 : 4 : 1	9	M
MC 20/0-1/4/1	20 : 0 : 20	1 : 4 : 1	7	S, M, F
MC 20/0-1/8/1	20 : 0 : 20	1 : 8 : 1	4	S, M, F

1) Based on the oven-dried weight of the particles. 2) Slow (1.3–1.6 mm/s), medium (2.1–2.9 mm/s) and fast (3.2–4.0 mm/s) for 0.5 g/cm^3 boards, and slow (1.3–1.5 mm/s), medium (2.3 mm/s) and fast (2.8–3.5 mm/s), correspondingly, for 0.7 g/cm^3 boards. 3) Boards were found to have inferior properties, thus omitted in subsequent analysis.

Table 2b. Processing variables for the conventional fiberboards.

Code	MC (%)	Particle proportions[1)]	Hot pressing method[2)]
Uniform mat MC			
10 MC-S	10	—	*A*
10 MC-F	10	—	*B*
10 MC-10/12	10	—	*C*
10 MC-8/12	10	—	*D*
Distributed mat MC	face/core/face	face/core/face	
MC 15/3-F	15 : 3 : 15	1 : 8 : 1	*B*
MC 15/3-8/12	15 : 3 : 15	1 : 8 : 1	*D*

1) Based on the oven-dried weight of the fibers. 2) *A*, *B*, normal hnt pressing at 160°C for 3 min, press closing speeds of 5.3–5.8 and 7.5–9.4 mm/s, respectively; *C*, *D*, two-step hot pressing at 160°C, with first step closing to 10 and 8 mm, respectively, then opening immediately to a final thickness of 12 mm, the total pressing time was 3 min.

test. Four IB specimens with dimensions of 50×50 mm were prepared from each board.

2.3 Results and discussion

Two main types of particleboards and fiberboards were produced successfully by manipulating the hot pressing method. Figure 2.1 shows some examples of the density profiles of homo-profile and conventional particleboards and fiberboards. The contrast in CD and PD in particleboard is greater at higher MD (Figs. 2.1a and 2.1b), but among all, this contrast is the greatest in fiberboard of lower MD (Fig. 2.1c). Figures 2.2a and 2.2b show that irrespective of the proportions of the face/core/face particles and press closing speed, the conventional particleboards produced from mats with distributed mat MC had substantially higher PD, but similar CD as those produced from uniform mat MC. In Fig. 2.2b, it can be seen that with similar mat MC distribution, faster closing speed did increase the PD to a certain extent at 0.5 g/cm^3 MD, but this difference diminished at higher MD. Fig. 2.2c shows the PD and CD of fiberboard to be affected by variations of hot pressing method and mat MC distribution to a greater extent at 0.5 g/cm^3 MD level compared to 0.7 g/cm^3. In both particleboard and fiberboard, CD and PD are highly correlated to MD linearly, with $R^2>0.984$.

2.3.1 Bending properties

(1) Homo-profile and conventional particleboards and fiberboards

Conventional fiberboard is expected to have higher MOE due to its highly densified surface layers, however, three-point static bending test showed that boards with conventional U-shaped density profile had similar MOE compared to homo-profile boards. In an additional measurement using free-free beam method, the dynamic MOE were found to be generally higher than static MOE, and the MOE of conventional fiberboard could be differentiated from homo-profile fiberboard. This is probably because dynamic method could reduce or eliminate exaggerated deformation caused by a great difference in PD and CD, as compared to static bending. In view of this, the values of dynamic MOE are used in the discussion for fiberboard hereafter.

Figures 2.3a and 2.3b show the MOR and MOE of both homo-profile particleboard and fiberboard to increase in a curvilinear trend with increasing MD or compaction ratio (CR). As shown in the figure, the MOR and MOE of both homo-profile and conventional particleboards exceeded the corresponding values of fiberboards. The performance of a consolidated product is mainly a reflection of the characteristics of its constituent elements. Particleboard which is composed of stiffer elements is therefore more rigid compared to fiberboard. Besides, at an equal oven-dried weight, particleboard has a better bonding efficiency, as it presents a lower specific surface area for inter-element bonding.

For homo-profile particleboard, the MOR and MOE could be represented by:

$$\mathrm{MOR}=-7.4+16\,\mathrm{MD}+48\,(\mathrm{MD})^2 \quad (R^2=0.990)$$

and

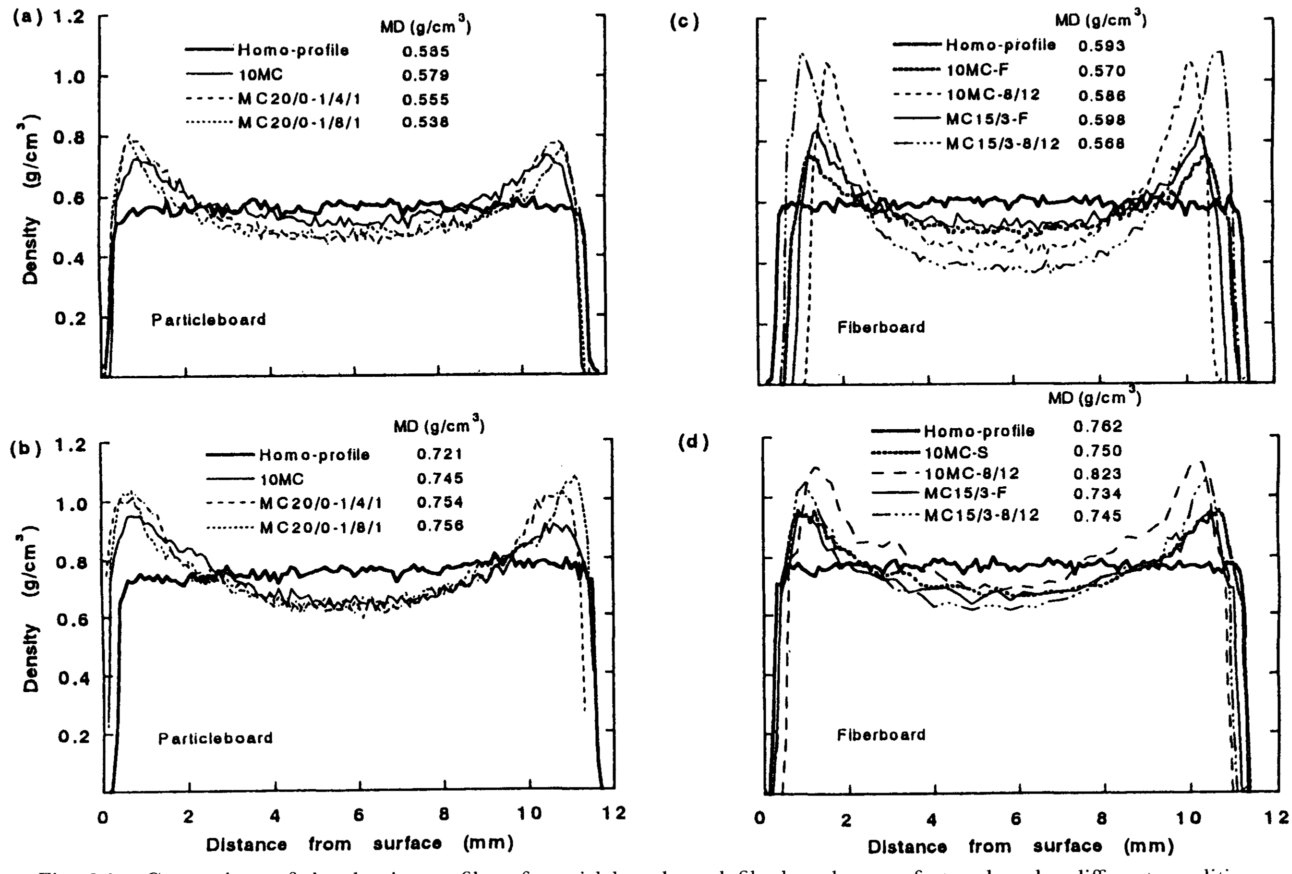

Fig. 2.1. Comparison of the density profiles of particleboards and fiberboards manufactured under different conditions.

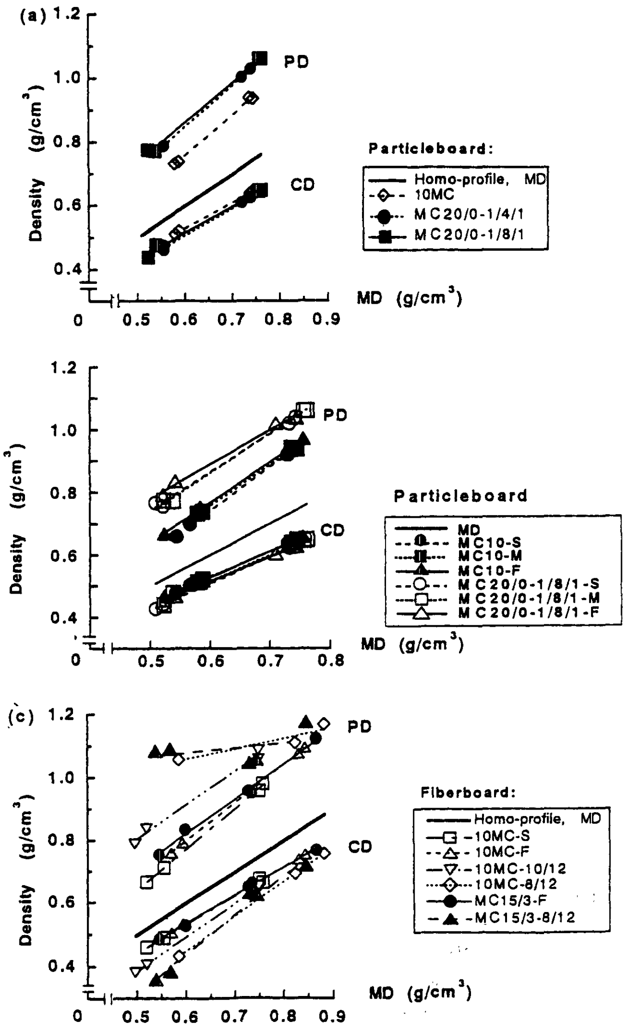

Fig. 2.2. Correlations among peak density (PD), core density (CD) and mean density (MD) in particleboard and fiberboard under different processing conditions.

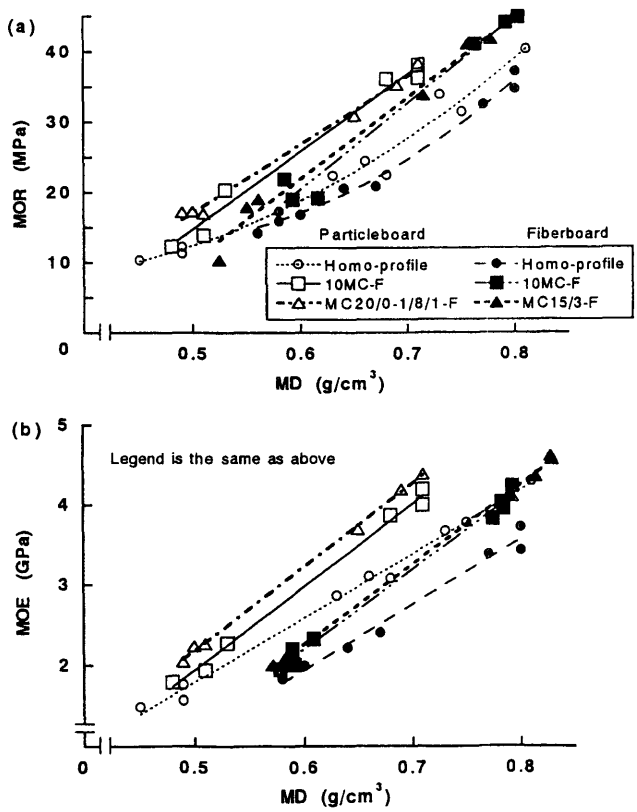

Fig. 2.3. Comparison of the moduli of rupture (MOR) (a) and elasticity (b) of conventional particleboard and fiberboard.

$$\text{MOE}=-1.2+4.0\,\text{MD}+3.5\,(\text{MD})^2\quad (R^2=0.988),$$

respectively. For fiberboard, these correlations were correspondingly,

$$\text{MOR}=1.6-20\,\text{MD}+77\,(\text{MD})^2\quad (R^2=0.996)$$

and

$$\text{MOE}=-0.9+2.7\,\text{MD}+3.8\,(\text{MD})^2\quad (R^2=0.994).$$

Extrapolation of both the MOR and MOE curves revealed the lower limit of particleboard density to be about 0.25–0.26 g/cm^3, below which the MOR and MOE would be negligible. For fiberboard, it was not possible to deduce the minimum MD based on the data of MOR obtained, but when MOE was equivalent to zero, the MD was calculated to be 0.25 g/cm^3, the same as that for particleboard.

Unlike in homo-profile boards, it could be misleading to correlate the bending strength of conventional boards directly with their MD. As shown in Fig. 2.3a, the MOR of conventional particleboard and fiberboard were found to exceed those of homo-profile boards by up to 32 and 37%, respectively, at equal MD. Both the homo-profile and conventional particleboards registered correspondingly higher MOR and MOE than fiberboards, but conventional fiberboard had higher MOR than homo-profile particleboard. As seen in the figure, the regression lines between MOR or MOE and MD for different types of boards tend to run parallel to each other, indicating nearly consistent differences of MOR and MOE between specific categories of board in terms of absolute magnitudes. The MOR and MOE of conventional particleboard were about 3–7 MPa and 0.6–1.0 GPa higher compared to conventional fiberboard.

For particleboard, results of statistical analysis revealed the MOE of MC20/0-1/8/1 to be significantly higher than that of 10 MC at all closing speeds. However, MC distribution was found to have significant effect on the board MOR at medium closing speed, but not at slow and fast closing speeds. The consistent improvement in MOE under different closing speeds and MD levels in response to the increase in PD shows that MOE is sensitive to, and highly dependent on, the board PD. In contradiction to MOE, the effect of PD on MOR is not consistent, because MOR is subjected to the effects of many other factors.

For fiberboard, both MOR and MOE generally decreased in the order of 10 MC-8/12, 10 MC-10/12, 10 MC-F and 10 MC-S, directly corresponding to the decreasing order of PD level (Fig. 2.2c), indicating a direct dependence of bending performance on PD. Irrespective of mat MC distribution, fiberboards produced using two-step hot pressing of 8/12 recorded higher MOR and MOE compared to single-step hot pressing at fast press closing speed. Despite having different mat MC distribution, all fiberboards produced using single-step fast press closing speed had similar MOR and MOE. Statistical analysis showed that irrespective of mat MC distribution, the MOR and MOE of fiberboards are significantly (99%) affected by hot pressing method.

(3) Specific effects of PD on MOR and MOE

Although the bending properties of composite boards may be subjected to the interactive influence of a number of density profile defining factors, the actual density profile of static bending specimen could not be determined due to its large dimensions. Since Pdi, GF and Pb are not related to MD, it is therefore only possible to estimate PD and CD based on the measured MD. When the production parameters were varied, variation in CD was not as high as in PD. Because of the high correlation of PD with bending properties at equal MD, PD was therefore selected for analyzing the specific/quantitative effects of density profile on bending properties based on the experimental data.

As shown in Fig. 2.4, for both particleboard and fiberboard, the MOR and MOE of 0.7 g/cm^3 boards were about 2 to 3 times the corresponding values at 0.5 g/cm^3,

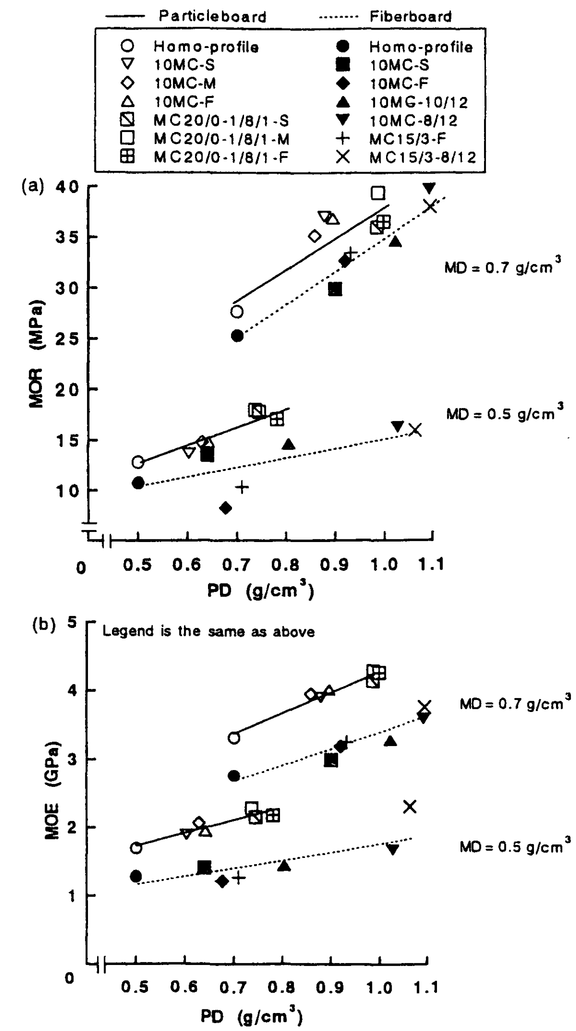

Fig. 2.4. Specific effects of peak density (PD) on the MOR (a) and MOE (b) of particleboard and fiberboard.

although the board might have almost equally high PD. Hence MD is still the most dominant factor influencing the overall bending performance of these composite boards, irrespective of the geometry of the constituent elements. The MOR and MOE of particleboard excelled those of fiberboard due to higher element stiffness and better bonding efficiency. PD seems to have a similar degree of specific effect on the MOR and MOE of both particleboard and fiberboard, as indicated by their respective PD-MOR and PD-MOE regression lines which run almost parallel to each other.

PD had a more acute effect on the MOR and MOE at higher MD level, as shown by a steeper gradient of the MOR-MD and MOE-MD regression lines, especially in the case of MOR (Fig. 2.4a). This reflects the curvilinear correlations between the MOR and MD based on homo-profile boards. The degree of scattering in MOR and MOE along these regression lines indicates that in addition to PD, the bending properties are also subjected to the effect of other factors. For fiberboard, a larger scatter is observed in the MOR-PD regression at 0.5 g/cm^3 MD, possibly because at lower MD, the low CD is more susceptible to the effect of shear due to inferior bonding among the loosely packed fibers. Thus the low density boards might have experienced flexural and shear failures simultaneously, resulting in rather unpredictable bending performance.

Based on the experimental data, at 0.5 g/cm^3 MD, the MOR of particleboard and fiberboard improved by up to 44 and 67% respectively, corresponding to 30 and 62% hike in MOE, when PD increased from 0.5 to 0.77 and 1.07 g/cm^3, respectively. Similarly, in 0.7 g/cm^3 boards, an increase of PD from 0.7 to 1.03 and 1.09 g/cm^3 in particleboard and fiberboard resulted in respective increases of 34 and 55% in MOR, and 30 and 34% in MOE.

2.3.2 IB strength and SWR

(1) Correlations between IB and MD or CD

Figure 2.5a shows the IB of both homo-profile and conventional particleboards and fiberboards to be curvilinearly correlated to MD. Below 1.0 g/cm^3 MD, irrespective of board type, particleboards had higher IB compared to fiberboards. Above 1.0 g/cm^3 MD, homo-profile fiberboards however, recorded a higher IB compared to homo-profile particleboard. This is because at an equal resin content, i.e., 8% based on the oven-dried weight of the particles/fibers, particleboard, which is composed of larger elements, presents a lower specific area for bonding, hence better bonding efficiency, compared to fiberboards. However, at higher MD, the more flexible and highly compressible fibers might have undergone a greater degree of plasticization and intermeshed together more closely under high pressure and temperature compared to particles, hence aiding inter-fiber bonding in addition to sole adhesive bonding.

The regression lines of IB-MD for both conventional particleboard and fiberboard fall below those for the corresponding homo-profile boards. This is due to the presence of a low-density core region in conventional boards where most failure occurred during vertical tensile test, hence recording lower IB values. Consequently, a more appropriate representation of IB would be IB-CD

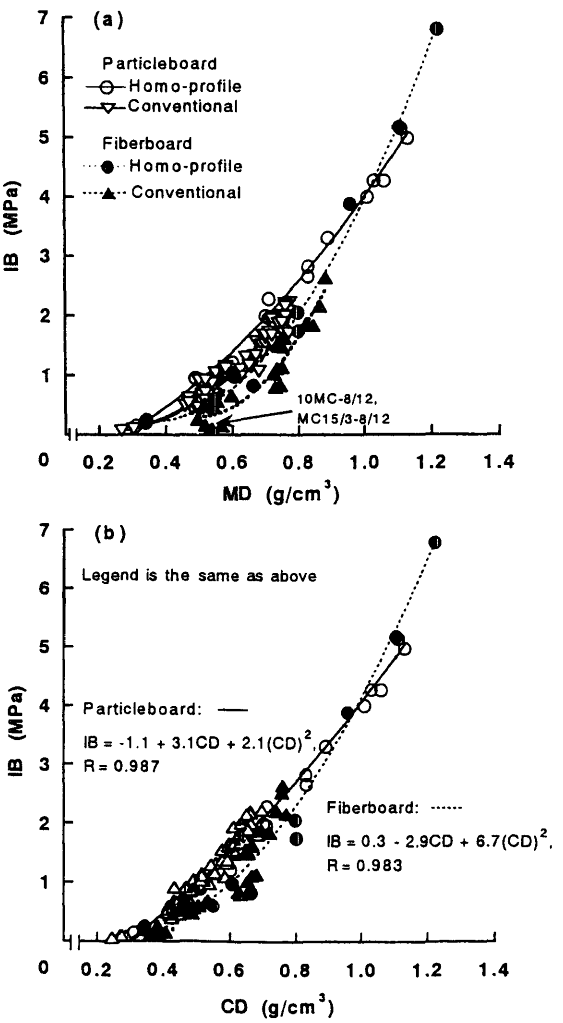

Fig. 2.5. Correlations of internal bond (IB) with mean density (MD) (a) and core density (CD) (b) in homo-profile and conventional particleboards and fiberboards.

correlations. As shown in Fig. 2.5b, irrespective of the board type and fabricating conditions, IB was on the whole, dependent on the board CD. In homo-profile boards which have a flat and uniform density profile, CD is in fact equivalent to MD.

The general correlations between IB and CD for particleboard and fiberboard can be expressed as:

$\mathrm{IB}=1.1+3.1\ \mathrm{CD}+2.1\ (\mathrm{CD})^2,\ R^2=0.974,$

and

$\mathrm{IB}=0.3\text{–}2.9\ \mathrm{CD}+6.7\ (\mathrm{CD})^2,\ R^2=0.966,$

respectively. Based on the above correlations, the bottom limits of the CD for particleboard and fiberboard are about 0.30 and 0.26 g/cm^3, respectively. These values are fairly close to those deduced based on MOR-MD and/or MOE-MD correlations, i.e., 0.25–0.26 and 0.25 g/cm^3, respectively. Despite presenting a lower total specific area for bonding, a higher CR is necessary in particleboard to improve inter-particle contact for the adhesive to spread over a greater particle surface area, instead of filling the voids in between the particles. The lower minimum value of CD for fiberboard compared to particleboard suggests

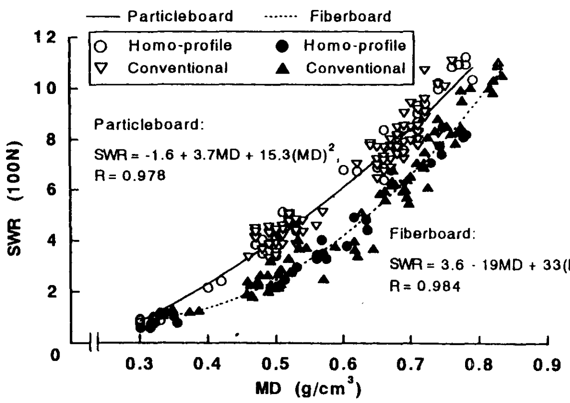

Fig. 2.6. Correlations of SWR with MD in homo-profile and conventional particleboards and fiberboards.

that a higher degree of felting in fibers does contribute to improved inter-fiber bonding. For practical application, the minimum CD is calculated to be 0.32 g/cm^3, thus the lower limit of board compaction ratio is higher than that reported previously[19], probably due to a lower resin content. However, with the latest advancements in resin adhesive and hot pressing technology, it has been reported that fiberboards with densities as low as 0.05 and 0.1 g/cm^3 could be manufactured successfully at 10% resin content[20–21].

(2) Correlations between SWR and MD

The SWR of both homo-profile and conventional particleboard and fiberboard were found to have very high correlations with MD, as shown in Fig. 2.6. These correlations in particleboard and fiberboards could be expressed as:

$\mathrm{SWR}=-1.6+3.7\ \mathrm{MD}+15.3\ (\mathrm{MD})^2,\ R^2=0.956,$

and

$\mathrm{SWR}=3.6\text{–}19\ \mathrm{MD}+33\ (\mathrm{MD})^2,\ R^2=0.968,$

respectively. In both particleboard and fiberboard, as board density, i.e., amount of mass per volume, increases, the ability of the board to hold or resist the withdrawal of screw was improved accordingly. At similar MD level, particleboard has higher SWR than fiberboard, probably due to a higher screw holding ability provided by the larger and less damaged wood elements compared to fibers, in addition to its better inter-particle bonding. Kimoto *et al.* also reported higher SWR in boards manufactured from larger particles[22].

In earlier work, no relationship was found to exist between density and SWR of some commercial particleboards, mainly due to the masking effect of the variations in board structure, particle size, resin type, species and processing conditions[4]. Unlike edge SWR which is more strongly affected by the board density profile, the high correlations between the SWR and MD despite the differences in board fabrication conditions/density profiles indicates that plane SWR is predominantly dependent on MD.

2.4 Summary

The effects of density profile on the mechanical properties of homo-profile and conventional particleboards and fiberboards were analyzed and compared. The results can be summarized as follows:

1) Homo-profile particleboard had similar MOR, but higher MOE compared to homo-profile fiberboard. Both the MOR and MOE were highly correlated to MD in a curvilinear trend. Conventional particleboard and fiberboard recorded higher MOR and MOE than corresponding homo-profile boards.

2) Distributed mat MC, which is more effective than press closing speed in forming a steep density profile, produced particleboard with higher MOE and MOR, especially at lower MD. Irrespective of mat MC distribution, two-step hot pressing of 8/12 produced fiberboard with the steepest density profile, corresponding to the highest MOE and MOR, especially at higher MD.

3) MD is the dominant factor affecting board bending properties. At 0.5 g/cm^3 MD, an increase of 0.1 g/cm^3 in PD could result in improvements of 2 and 1.1 MPa in the MOR, corresponding to 0.2 and 0.1 GPa improvements in the MOE of particleboard and fiberboard, respectively. At 0.7 g/cm^3 MD, the corresponding increases in the MOR and MOE were 3.1 and 3.5 MPa and 0.3 and 0.2 GPa in particleboard and fiberboard, respectively.

4) Irrespective of board type, IB was highly correlated to CD, and particleboard generally had higher IB compared to fiberboard. SWR was found to be dependent on the board MD, not density profile. The SWR of particleboard was higher than fiberboard.

Chapter 3 Analysis of the Specific Effect of Density Profile on Bending Performance using Finite Element Method

In actual experiments of composite board fabrication, it is difficult to manipulate the variation of a specific part of density profile, while keeping the others constant. As a result, the variations of board properties are always subjected to the interactive effect of several defining factors, rather than a single factor. In addition, it had also been not possible to obtain some density profiles, e.g., with PD up to 1.5 g/cm^3, within our experimental limits. Two dimensional finite element method (FEM) was therefore applied to clarify the specific profile factors-bending property correlations, via numerical analysis of various density profile models which enable modification(s) of specific profile portion(s) to be better controlled.

3.1 Methods

3.1.1 Fundamental data

In the FEM computer simulation, conventional particleboard and fiberboard are considered to be composed of thin layers of homo-profile boards with various mean densities. In this regard, the fundamental data input are based on the basic properties of homo-profile boards. The properties determined for FEM analysis include MOE along the horizontal plane (E_x) and thickness (E_y), and the shear rigidity (G_{xy}).

For homo-profile particleboard, E_x was measured by destructive static bending test where the 12 mm thick samples were cut into 40 by 200 mm, and the bending test was conducted over an effective span of 180 mm, at a loading speed of 10 mm/min. Since the experimental E_x of conventional fiberboard was obtained using dynamic F-F beam method, the E_x input for FEM analysis was also based on the dynamic values measured using the same method.

The dynamic E_y of both homo-profile particleboard and fiberboard were determined by using F-F beam method. The samples for E_y were prepared by gluing 8 pieces of 12 mm thick, 10 by 17 mm specimens face to face, using epoxy resin. In a preliminary experiment, the presence of epoxy glue-lines was found to have no effect on the E_x measured for cut-and-glued specimens, compared to those of uncut specimens. In measuring the E_x and E_y using free-free flexural method, these values were calculated based on the first mode of resonance frequency.

For homo-profile particleboard, G_{xy} was determined by using tapping method, where samples with the same dimensions as E_x samples were hung at two ends to allow

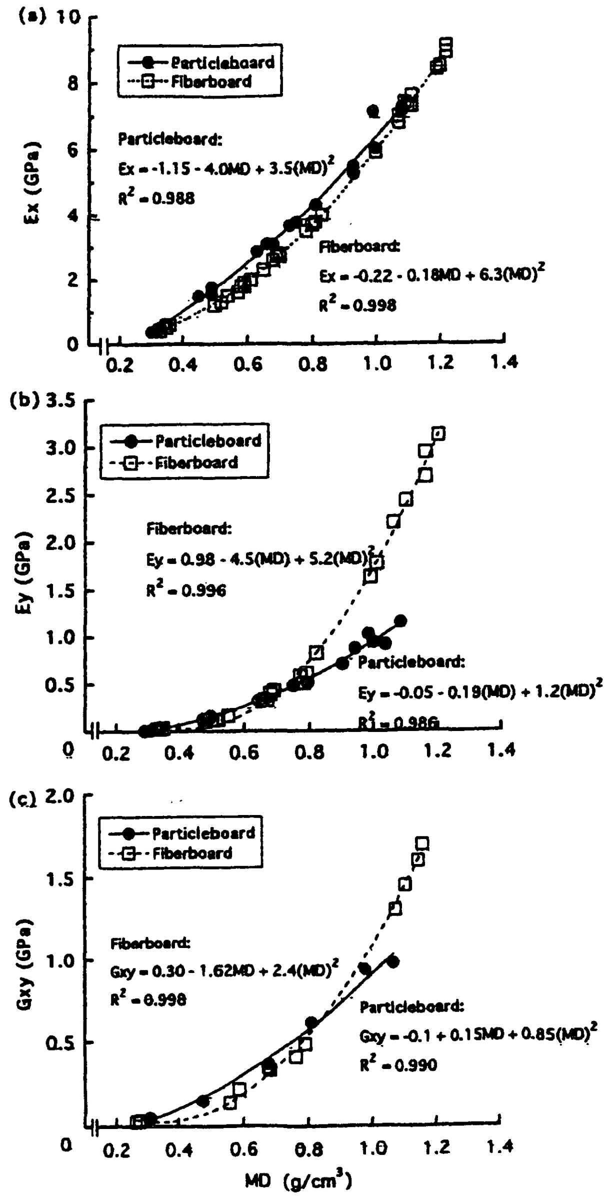

Fig. 3.1. Moduli of elasticity along the x-axis (E_x) (a) and thickness (E_y) (b), and shear rigidity (G_{xy}) of homo-profile particleboard and fiberboard.

free movement. A hammer was used to hit at one end, and the resonance frequencies for the first and fourth modes of vibration were determined. The G_{xy} was calculated using the Timoshenko-Goens-Hearmon method which takes into consideration the resultant shear deformation and moment of inertia[23–24]. For homo-profile fiberboard, torsion method was used to determine the G_{xy}. The correlations of E_x, E_y and G_{xy} with MD in homo-profile particleboard and fiberboard are as shown in Fig. 3.1.

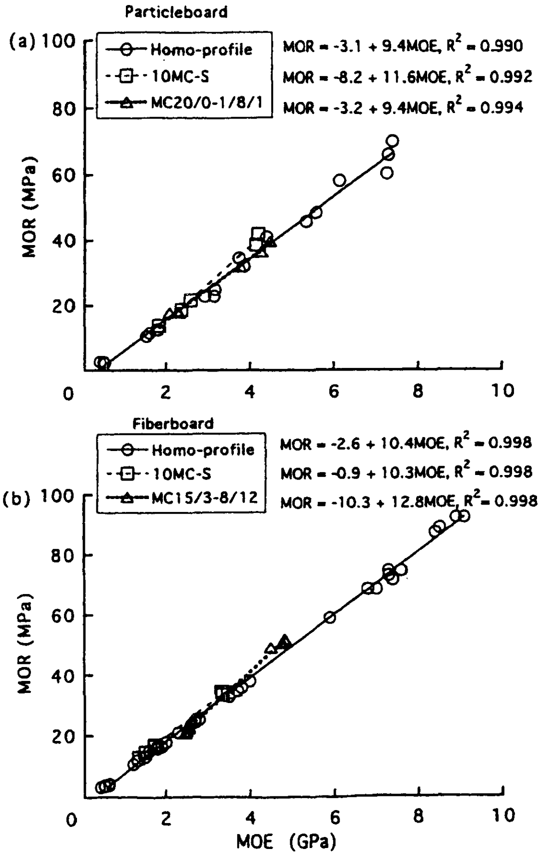

Fig. 3.2. Correlations between moduli of elasticity (MOE) and rupture (MOR) in particleboard (a) and fiberboard (b).

3.1.2 FEM Model

Figure 3.2 shows the correlations between MOE and MOR in homo-profile and conventional particleboards and fiberboards. Since MOR is highly correlated to MOE, it is therefore possible to estimate the MOR based on MOE. Hence, only MOE is discussed in the following sections. Earlier results indicate the net impact of PD on MOR and MOE to be greater at higher MD level (Section 2.3.1 (2)). Therefore, further analyses on the effects of density profile on the bending properties of particleboard and fiberboard were based on a MD of 0.7 g/cm^3.

For FEM analysis, stress distribution within the static bending specimen is considered to be symmetrical on both sides of the loading point, and the density profile is considered to be symmetrical along the center line of the 12 mm thick board, i.e., at 6 mm from the board surface. For simplicity, the calculation was based on the left half of actual bending system, as illustrated in Fig. 3.3. The 6 mm thick section was divided into elements of 0.1×0.2 mm in 3 mm from the surfaces, and the rest was of 0.2×0.2 mm. The total number of elements and nodes are 45,000 and 45,591, respectively. The FEM calculation was based on a total load of 98 N for the bending system. The total deflection (δ) takes into consideration deflections due to bending and shear, and the MOE is calculated as shown in equation [1][25].

$$\delta = \delta_{bend} + \delta_{shear} = \frac{Pl^3}{48EI}\left[1 + \frac{3E}{2G}\left(\frac{h}{l}\right)^2\right] \qquad [1]$$

Where,

δ = total deflection under a load of 98 N (m)
δ_{bend} = deflection due to bending
δ_{shear} = deflection due to shear
P = load (98 N) - in overall bending system
l = length (1.8×10^{-1} m)
E = modulus of elasticity (Pa)

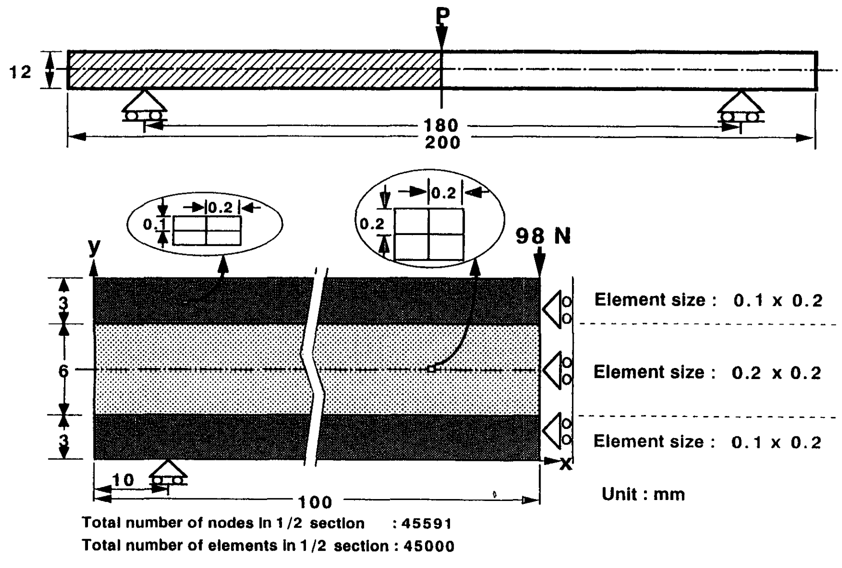

Fig. 3.3. Finite element idealization for 1/2 section of the static bending system.

I = moment of inertia of area

$= \frac{bh^3}{12}$

b = board unit width (1×10^{-3} m)

h = board thickness (1.2×10^{-2} m)

$G = \frac{1}{h} \Sigma G_i h_i$, G_i is the shear rigidity of every layer of 10^{-4} m, h_i = thickness of each layer (10^{-4} m).

3.1.3 Reliability of calculation using FEM

To ascertain the reliability of calculating board MOE using the FEM program, the calculated MOE of homo-profile and conventional particleboards and fiberboards with MD of 0.5 and 0.7 g/cm^3, were determined and compared with experimental MOE.

3.1.4 Design of density profile models

Based on the profiles of conventional boards produced earlier, a series of modifications were made to certain part of the profile, while keeping the others constant as far as possible. The quantitative effect of each different portion of density profile on the board properties was then analyzed by calculating the board MOE using FEM.

(1) Effect of PD

In determining the effect of PD on the bending performance of particleboard and fiberboard, the PD was varied from 1.0 to 1.5 g/cm^3, which is the maximum possible density, equivalent to that of wood substance's. The density profiles with different PD are shown in Fig. 3.4a. The PA of all models were adjusted to be the same despite the changes in PD and shape of the peak, and the profile of core region was kept constant in all cases. In addition, a profile with a slimmer peak at 1.5 g/cm^3 PD, but more leveled core region (PD7-slim) was included to see the effect of peak width on MOE. The PA was also adjusted to be the same as the other models.

(2) Effect of Pdi

For the effects of Pdi on board bending properties, PD was fixed at 1.5 g/cm^3, while Pdi was varied from 0.2 to 2.0 mm from the board surface. All the models were adjusted to have the same PA, with the same core profile, as shown in Fig. 3.4b. In actual experiment, the value of Pdi in particleboard and fiberboard was found to vary between 0.4–0.9 mm, depending on the mat MC distribution and hot pressing method.

(3) Idealized density profile

To determine the optimum density profile, an idealized model for density profile was proposed, where the density profile was divided into 2 symmetrical halves each

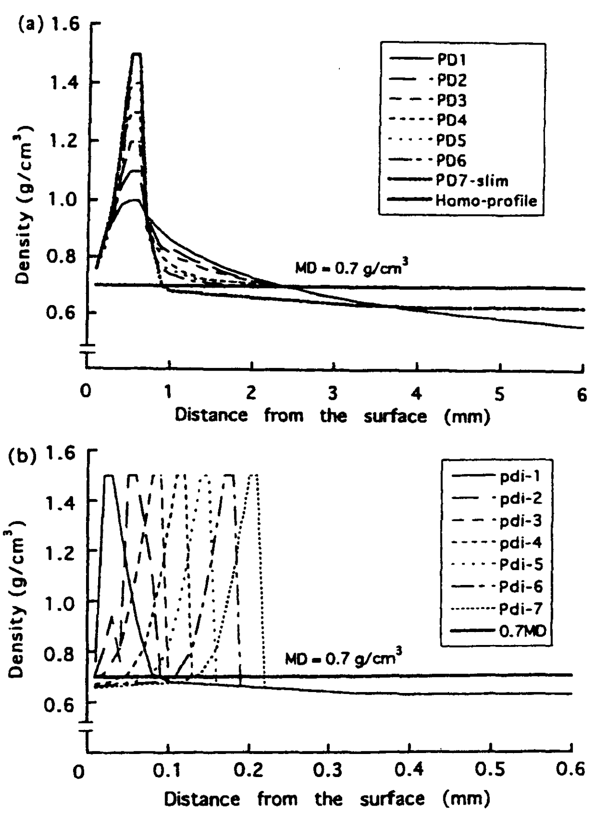

Fig. 3.4. Density profile models for variations in peak density (a) and peak distance (b).

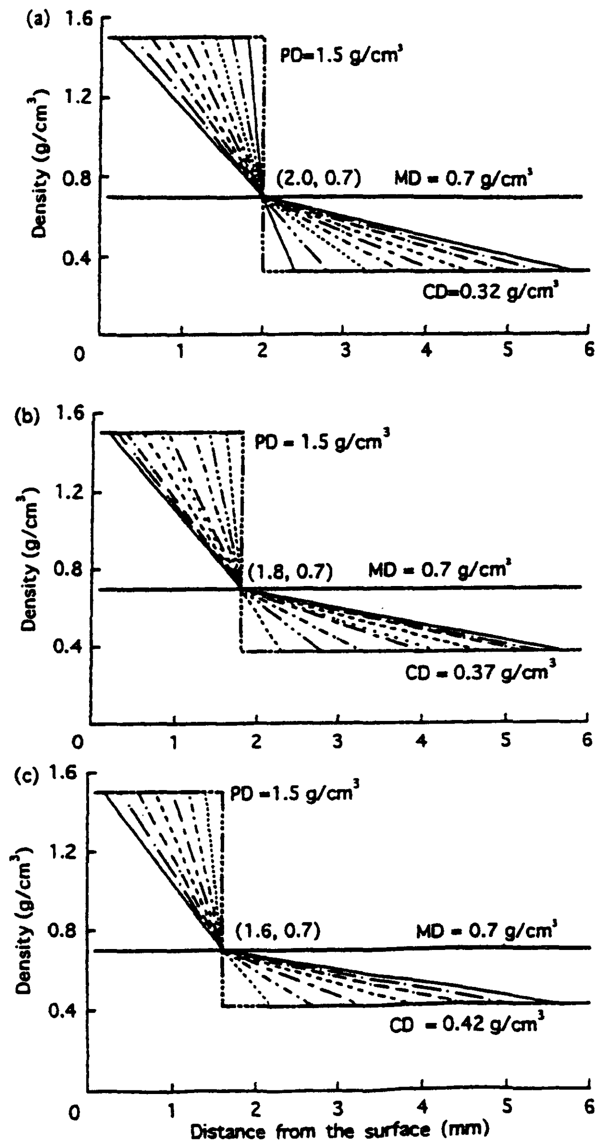

Fig. 3.5. Idealized density profile models for particleboard and fiberboard(*) with internal bond strengths of 0.13 (a), 0.3 (b) and 0.5 (c) MPa, respectively.

consisting of 3 sections, i.e., peak, slope and core regions, defined by straight lines. The peak area was increased by increasing the width of the peak, and similar adjustment was made to the core, based on the "cut-and-fill" principle. All models have the same MD of 0.7 g/cm^3. Three series of density profiles were produced, based on a PD of 1.5 g/cm^3. For particleboard, CD was calculated based on JIS A5908 standard IB strength requirements of 0.15, 0.3 and 0.5 MPa, corresponding to 0.32, 0.37 and 0.42 g/cm^3, as shown in Figs. 3.5a, 3.5b and 3.5c, respectively (IB$=-7.4+19.4$ CD$+29$ (CD)^2). For fiberboard, the corresponding CD were 0.34, 0.44 and 0.48 g/cm^3, based on corresponding JIS A5905 standard IB strength requirements of 0.2, 0.4 and 0.5 MPa (IB$=0.3-2.9$ CD$+6.7$ (CD)^2).

3.2 Results and discussion

Fig. 3.6 shows that MOE of particleboards and fiberboards could be calculated using two-dimensional FEM with good reliability, with less than 6% deviation from experimental MOE values. It is therefore possible to analyze the effects of various density profile defining factors on the bending properties by calculating the MOE of different density profile models using FEM.

3.2.1 Effect of PD

Fig. 3.7 shows an example of the comparison of bending

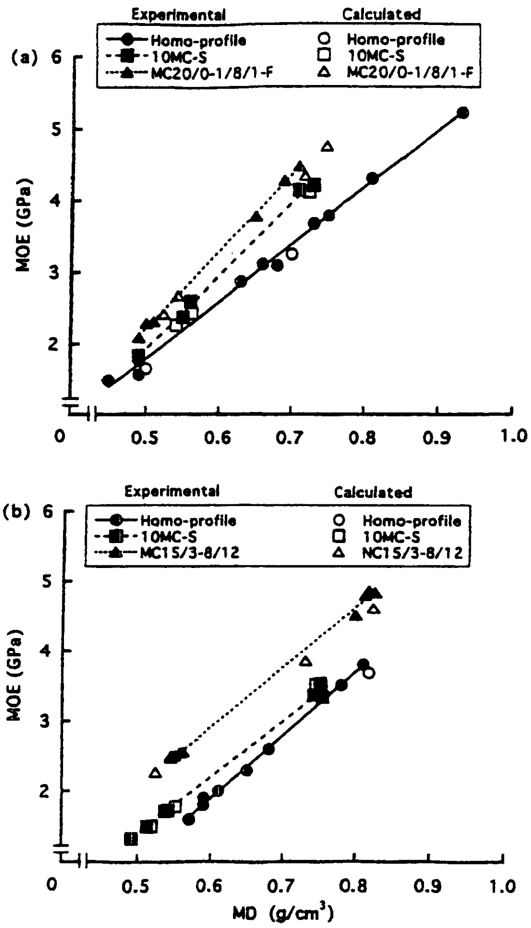

Fig. 3.6. Comparison of the experimental and calculated moduli of elasticity (MOE) for various particleboards (a) and fiberboards (b).

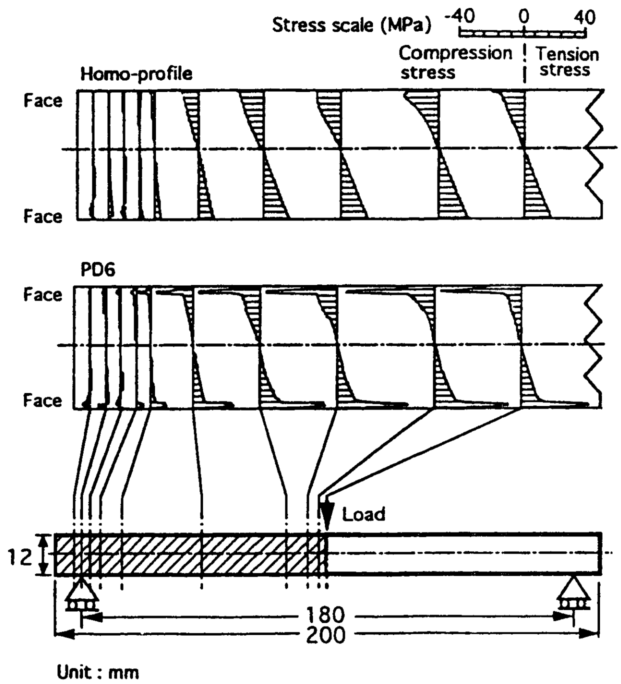

Fig. 3.7. Normal stress distributions in homo-profile and PD6 particleboards with different density profiles.

stress distribution across the board thickness in particleboard of 0.7 g/cm^3 homo-profile, and density profile model with 1.5 g/cm^3 peak (PD6). The maximum bending stresses in homo-profile board are relatively low compared to those in PD6. The strength of a material is directly related to its density. Since the regions near the surfaces of PD6 are composed of high PD, its ability to withstand higher bending stress is consequently upgraded. The resistant bending moment of the face (M_f) is obtained by

$$M_f=\sigma_f A_f y_f \qquad [2]$$

where σ_f=normal stress, A_f=cross sectional area of the face, and y_f=distance from the neutral axis. High density sections near the board surfaces result in higher M_f, which gives rise to reinforcement effect near the surfaces.

Figure 3.8 shows the specific effects of PD on MOE in particleboard and fiberboard. The correlation between PD and MOE for PD ranging from 0.7 to 1.1 g/cm^3 were based on the experimental data, while those for PD exceeding 1.1 g/cm^3 were based on FEM calculation. Except for the absolute magnitude, PD-MOE correlations of particleboard and fiberboard generally follow the same trend, i.e., MOE increases drastically when PD increased from 0.7 up to about 1.1 g/cm^3, but the improvement effect of PD on MOE reduced significantly at above 1.1 g/cm^3 PD.

Compared to calculated data, the experimental data show a greater degree of scattering in the MOE-PD correlation. This may be due to the interference of variations in other profile defining factors together with the variation in PD, e.g., Pdi and CD. In the density profile models for FEM calculation, the level of PD was adjusted with Pdi and core region remaining unaltered throughout. However, any increment in PD was inevitably accom-

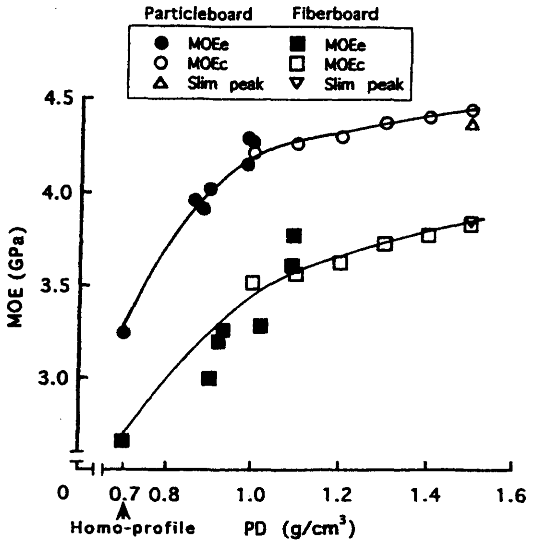

Fig. 3.8. Effect of peak density (PD) on the modulus of elasticity (MOE) of particleboards and fiberboards. Notes: MOEe, experimental MOE; MOEc, calculated MOE.

panied by a simultaneous reduction in peak width near the peak base. Consequently, the resultant variation in MOE was mainly, but not solely, due to the changes in PD. Calculation by FEM revealed that despite having equal PD with higher CD, a reduction in peak width could result in a reduction of about 4% in the MOE of particleboard, but not fiberboard (Fig. 3.8). Consequently, at higher PD, the actual improvement effect of PD on MOE could have been counteracted by the simultaneous reduction in peak width, which has a detrimental effect on MOE, especially in particleboard.

Based on the experimental data, the MOE of particleboard and fiberboard could be increased by about 30 and 40%, respectively, with corresponding increments of PD from 0.7 to 1.0 and 1.1 g/cm^3. At above 1.0/1.1 g/cm^3 PD, an increase of PD from 1.0/1.1 to 1.5 g/cm^3 resulted in merely about 6 and 9% increments in MOE for particleboard and fiberboard, respectively. This shows that beyond 1.0 or 1.1 g/cm^3 of PD in particleboard and fiberboard, respectively, MOE could still be improved by increasing the PD, but the effectiveness of improvement was much lower, compared to at lower range of PD.

3.2.2 Effect of Pdi

From Fig. 3.9a, it can be seen that MOE decreases proportionally as the peak moves further away from the board surface. To avoid the interruption of bending stress distribution arising from the loading and supporting points, as an example, the stress distributions in $x=55$ mm were extracted and compared, for three particleboard models with different Pdi, as shown in Fig. 3.9b. Based on the similar theory of M as mentioned above, Pdi-1, being located furthest away from the neutral axis, resulted in the highest MOE. For particleboard, doubling Pdi from 1 to 2 mm could result in a reduction of about 11% in MOE, while a reduction of 12% was recorded in fiberboard, under the same Pdi increment.

3.2.3 Optimum density profile

Fig. 3.10 shows the correlations between PA and calculated MOE for various idealized density profile models of particleboard and fiberboard, based on different CD. At similar MD of 0.7 g/cm^3, the MOE of particleboard with CD ranging from 0.32 to 0.42 g/cm^3 were about 2 GPa higher compared to fiberboard with 0.34–0.48 g/cm^3 CD. At the minimum CD of 0.32 and 0.34

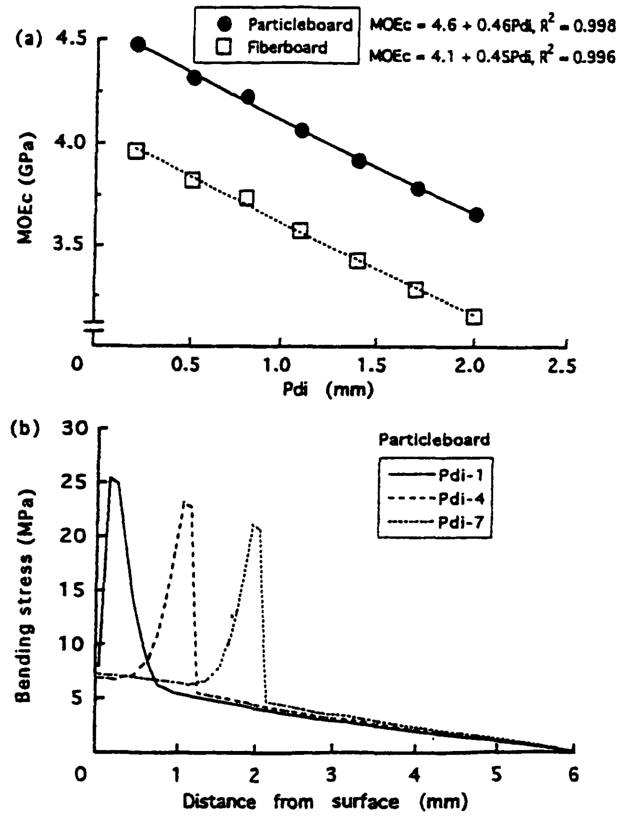

Fig. 3.9. Effect of peak distance (Pdi) on the modulus of elasticity (MOE) (a) and bending stress (b) of particleboard and fiberboard.

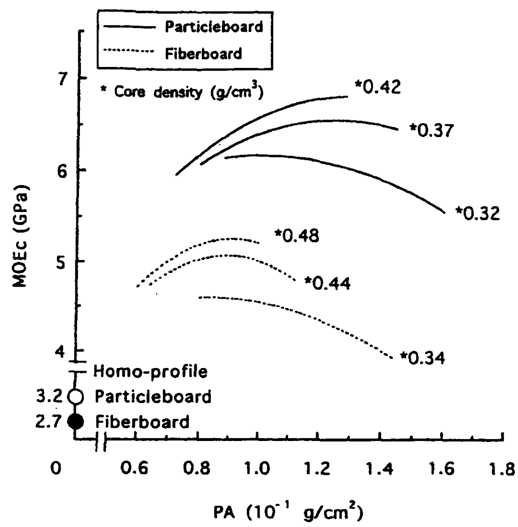

Fig. 3.10. Variation of calculated modulus of elasticity (MOEc) with respect to peak area (PA) in idealized density profile models of particleboard and fiberboard.

Table 3. Correlations among various density profile defining factors

	MD	CD	PD	Pdi	GF	Pb	PA
Particleboard							
MD	1.0000						
CD	0.9894**	1.0000					
PD	0.8590**	0.9186**	1.0000				
Pdi	0.0503	−0.0246	−0.2446	1.0000			
GF	−0.3901*	−0.3002	0.0497	−0.7193**	1.0000		
Pb	0.1674	0.0847	−0.1791	0.5902**	−0.6796**	1.0000	
PA	0.4900**	0.5844*	0.8122	−0.2821	0.3406*	−0.1130	1.0000
Fiberboard							
MD	1.0000						
CD	0.9638**	1.0000					
PD	0.7549**	0.5619**	1.0000				
Pdi	0.1459	0.2316	−0.1913	1.0000			
GF	−0.3799*	−0.4505	0.0255	−0.7458**	1.0000		
Pb	0.4754*	0.5042*	0.1811	−0.0435	−0.3520*	1.0000	
PA	−0.0214	−0.2744	0.6319**	0.4884*	0.4676*	−0.1611	1.0000

*, significance level ≤95% ; **, significance level ≤99% ; MD, mean density ; CD, core density ; PD, peak density ; GF, gradient factor ; Pdi, peak distance ; Pb, peak base ; PA, peak area.

g/cm^3, the MOE of both particleboard and fiberboard began to drop when the PA was increased, i.e., when the gradient of transition zone was increased. For particleboard and fiberboard with higher CD of 0.37, and 0.44 and 0.48 g/cm^3, respectively, the MOE increases to a maximum gradually, then falls, despite further rise in PA. For particleboard with 0.42 g/cm^3 CD, the MOE was found to increase rapidly with an increase in PA initially, then leveled off, up to the vertical transition zone. Based on idealized profile models, the optimum PA for particleboard with IB of 0.15 and 0.3 MPa were 0.1 and 0.124 g/cm^2, respectively. For IB of 0.5 MPa, the rectangular density profile was found to have no detrimental effect on the MOE of particleboard. For fiberboard with IB of 0.4 and 0.5 MPa, the difference in the optimum PA was minimal, i.e., 0.89 and 0.91 g/cm^2, respectively. For both particleboard and fiberboard, as the board CD increases, the optimum PA tended to shift upwards hyperbolically.

In bending, bending and shear stresses are concentrated near the faces and core, respectively. Theoretically, an increase in PA is synonymous to an increase in cross sectional area, i.e., A in equation [1]. Within the elastic limit, taking the shear stress distribution at $x=55$ mm section for particleboard model with 0.37 g/cm^3 CD (Fig. 3.5b) as an example, it was found that despite having a larger PA, the model consisting of rectangular peak and core sections (peak tip=1.8 mm) experienced a higher shear stress nearer to the surfaces compared to the model with 1.2 mm peak tip. Should the load be increased to a point where the sample fails, this shear stress may be further amplified, and shear failure may initiate at the steep boundary between the peak and core regions, resulting in lower MOE of the rectangular model. Where CD is higher at 0.42 g/cm^3, the occurrence of shear could be prevented, despite a steep transition between the peak and core regions. Consequently, PA could be increased to the maximum to achieve the optimum bending strength. In the case of fiberboard which has lower MOE than particleboard, the effect of transition zone gradient is even more critical, as a reduction in MOE was still recorded at the maximum PA, despite having a higher CD of 0.48 g/cm^3. For both particleboard and fiberboard, the lower the CD, the gentler the transitional zone between the face and core should be, in order to prevent shear deformation/failure during bending.

3.2.4 Critical factors affecting MOE

The MOE of particleboard and fiberboard samples with varied conventional density profiles at 0.5 and 0.7 g/cm^3 MD were calculated using FEM. Multiple regression analysis was then conducted to correlate the MOE with various density profile defining factors. Based on a minimum improvement of 1% in R^2 as each additional factor was included, the MOE of conventional particleboard and fiberboard could be expressed as:

$$\mathrm{MOE}=7.6\,\mathrm{MD}+1.9\,\mathrm{PD}-0.04\,\mathrm{Pdi}-2.9,\quad R^2=0.998,$$

and

$$\mathrm{MOE}=16\,\mathrm{MD}-6.3\,\mathrm{CD}-3.9,\quad R^2=0.983,$$

respectively. It can be concluded that the MOE of particleboard is most affected by MD, followed by PD and Pdi. In fiberboard, however, as far as MOE is concerned, MD has the most dominant effect, followed by CD. This may indicate the effect of shear deformation caused by a big contrast in PD and CD on the MOE of fiberboard.

3.3 Summary

At 0.7 g/cm^3 MD, increasing PD from 0.7 to 1.0 and 1.1 g/cm^3 could result in 30 and 40% improvement in the MOE of particleboard and fiberboard, respectively. At above 1.0 and 1.1 g/cm^3 PD, with further increment of PD up to 1.5 g/cm^3, the MOE of particleboard and fiberboard could only be improved by about 6 and 9%, respectively. Higher Pdi generally results in reduced MOE. Increasing Pdi from 1 to 2 mm resulted in 11 and 12% reduction in the MOE of particleboard and fiberboard, respectively.

For both particleboard and fiberboard, the effect of the density profile gradient on the MOE is dependent on the level of CD. At lower CD, the density profile should be gentler in order to prevent the occurrence of shear failure at

PD-CD transitional zone. The MOE of fiberboard is more susceptible to the detrimental effect of density profile gradient compared to particleboard, despite having similar IB and higher CD.

Based on multiple regression analysis, the MOE of particleboard and fiberboard could be defined by:

$$\mathrm{MOE}=7.6\ \mathrm{MD}+1.9\ \mathrm{PD}-0.04\ \mathrm{Pdi}-2.9,\ R^2=0.998,$$

and

$$\mathrm{MOE}=16\ \mathrm{MD}-6.3\ \mathrm{CD}-3.9,\ R^2=0.983,$$

respectively.

Conclusions

Two types of particleboards and fiberboards were manufactured from lauan (*Shorea* spp.) particles/fibers, namely homo-profile and conventional boards which have flat and uniform, and typical U-shaped density profiles along the board thickness, respectively. The resin adhesive used was isocyanate resin, at 8% resin content level. Homo-profile boards were manufactured at 0.3–1.1 g/cm^3 MD, whereas conventional boards were produced at 0.5 and 0.7 g/cm^3 MD. For conventional boards, the mat MC level and distribution, and hot pressing method were manipulated to obtain boards with varied density profiles. The density profiles of boards were measured by using a gamma ray densitometer, and the board mechanical properties were evaluated. The correlations among processing variables, density profile, and board properties were subsequently established and compared. Two-dimensional FEM was applied to further clarify the specific effects of PD and Pdi on the bending properties of board. An attempt was also made to determine the optimum density profile for particleboards and fiberboards with varied IB, based on MOE calculated for the idealized density profile models.

Among the selected manufacturing factors, mat MC distribution and two-step hot pressing of 8/12 resulted in the steepest density profile in particleboard and fiberboard, respectively. In both particleboard and fiberboard, the CD and PD are highly correlated to MD, at 99% significance level. Generally, PD could be modified to a greater extent, with limited variation in CD.

Evaluation of the board performances revealed that particleboard and fiberboard are two products with basically different mechanical properties. While the mechanical properties of these composite boards showed similar dependence on MD and density profile, particleboards generally had superior properties/strengths compared to fiberboards. The bending properties of particleboards and fiberboards could be improved by increasing the PD, but the effectiveness of improvement reduced gradually at higher PD. Based on the experimental data, at 0.5 g/cm^3 MD, the MOR of particleboard and fiberboard improved by up to 44 and 67% respectively, corresponding to 30 and 62% hike in MOE, when PD increased from 0.5 to 0.77 and 1.07 g/cm^3, respectively. Similarly, in 0.7 g/cm^3 boards, an increase of PD from 0.7 to 1.03 and 1.09 g/cm^3 in particleboard and fiberboard resulted in respective increases of 34 and 55% in MOR, and 30 and 34% in MOE. Irrespective of board type, IB was highly correlated to CD, whereas SWR was found to be dependent on the board MD, not density profile. In general, particleboard had higher IB and SWR compared to fiberboard at equal MD.

The MOE values of particleboards and fiberboards calculated by using FEM showed less than 6% deviation from the experimental values. Based on MOE calculated for the density profile models, at above 1.0 and 1.1 g/cm^3 PD, with further increment of PD up to 1.5 g/cm^3, the MOE of particleboard and fiberboard could only be improved by about 6 and 9%, respectively. Analysis of the idealized density profile shows that for both particleboard and fiberboard, the gradient of the density profile is dependent on MD and CD. At lower MD where CD is low, the density profile should be gentler in order to prevent the occurrence of shear failure. The optimum transition gradient between PD and CD could be deduced based on the correlations between MOE and PA. Higher Pdi generally results in reduced MOE. Increasing Pdi from 1 to 2 mm resulted in 11 and 12% reduction in the MOE of particleboard and fiberboard, respectively.

Acknowledgements

The author is indebted to Prof. Dr. Shuichi Kawai for his invaluable guidance and untiring advice throughout the course of this study.

Sincere thanks are due to Tohbek Co. and Hokushin Co. for their generous contributions of research raw materials and kind support.

The unfailing assistance of Dr. Zhang M, Dr. Wang Q, Dr. Yang P, Ms Han, Ms Kawasaki T and Mr. Hata Toshihiro is also gratefully acknowledged. Special appreciation is directed to Dr. Umemura K, Dr. Obataya E and Mr. Bossev DP for their constant support and constructive suggestions. Many thanks also go to all Senseis at WRI, and all friends/colleagues for their direct or indirect contributions.

References

1) F.F.P. Kollmann, E.W. Kuenzi and A.J. Stamm: Principles of wood science and technology, Vol II. Wood based materials. Springer, Berlin, Heidelberg, New York, p. 312, 339, 559–564 (1975).
2) O. Suchsland and G.E. Woodson: Fiberboard manufacturing practices in the United States. Agricultural Handbook, No. 640, Forest Service, US Department, Wisconsin, p. 136–148 (1986).
3) T.M. Maloney: Modern particleboard and dry-process fiberboard manufacturing. Miller Freeman Publications Inc, California, p. 158–177 (1977).
4) M.W. Kelly: Critical literature review of relationships between processing parameters and physical properties of particleboard. General Technical Report FPL-10, Forest Products Laboratory, US Department of Agriculture, Wisconsin, pp. 65 (1977).
5) F. Kollmann: The influence of differences in moisture-content of wooden partiles, before the pressing, upon the properties of chipboards. *Holzals Roh- und Werkstoff,* **15**, 35–44 (1957).
6) M. Iwashita, T. Matsuda and S. Ishihara: The influence of differences in moisture content of wooden particles upon the pressing of particle boards. *Wood Industries,* **14**, 376–382 (1959).
7) M.D. Strickler: Effect of press cycles and moisture

content on properties of Douglas-fir flakeboard. *For. Prod. J.*, **9**(7), 203–215 (1959).

8) S. Kawai and H. Sasaki: Production technology for low-density particleboard. I. Forming a density gradient and its effect on board properties. *Mokuzai Gakkaishi,* **32**(5), 324–330 (1986).
9) R.R. Stevens: Slicing apparatus aids in determination of layer density of particleboard. *For. Prod. J.*, **28**(9), 51–52 (1978).
10) K.C. Shen and M.N. Carroll: Measurement of layer-strength distribution in particleboard. *For. Prod. J.*, **20**(6), 53–55 (1970).
11) P.R. Steiner, L.A. Jozsa, M.L. Parker and S. Chow: Application of x-ray densitometry to determine density profile in waferboard: Relationship of density to thickness expansion and internal bond strength under various cycles. *Wood Sci.,* **11**(1), 48–55 (1978).
12) T.L. Laufenberg: Using gamma radiation to measure density gradients in reconstituted wood products. *For. Prod. J.*, **36**(2), 59–62 (1986).
13) P.M. Winistorfer, E.V.C.M. Depaula and B.L. Bledsoe: Measuring the density profile during pressing: the method, the equipment, and the results. In: Maloney TM (ed) Proceedings of the 27th International Particleboard/Composite Material Symposium. Washington State Univ, Pullman, p. 45–53 (1993).
14) S. Dueholm: Determination of density profile of wood-based panels: from traditional off-line laboratory techniques to continuous, in-line, real-time monitoring. In: Wolcolt MP (ed) Proceedings of the 30th International Particleboard/Composite Material Symposium. Washington State Univ, Pullman, p. 45–57 (1996).
15) M. Zhang, S. Kawai, H. Sasaki, T. Yamawaki, Y. Yoshida and M. Kashihara: Manufacture and properties of composite fiberboard. *Mokuzai Gakkaishi,* **41**, 903–910 (1995).
16) Anon: Japanese Industrial Standard - Particleboards (JIS A5908). Japanese Standards Association (1994).
17) Anon: Japanese Industrial Standard - Fiberboards (JIS A5905). Japanese Standards Association (1994).
18) D.W. Haines, J.M. Leban and C. Herbe: Determination of Young's modulus for spruce, fir and isotropic materials by the resonance flexure method with comparisons to static flexure and other dynamic methods. *Wood Sci. and Technol.,* **30**, 253–263 (1996).
19) S. Kawai and H. Sasaki: Low density particleboard. In: Shiraishi N, Kajita H, Norimoto M (eds). Recent Research on Wood and Wood-based Materials. Elsevier Science Publishers LTD and The Society of Material Science, Japan, p. 33–41 (1993).
20) T. Kawasaki, M. Zhang and S. Kawai: Manufacture and properties of ultra-low-density fiberboard. *J. of Wood Sci.,* **44**(5), 354–360 (1998).
21) S. Kawai, D. Eusebio, M. Wallen and H. Sasaki: Production of low density fiberboard using foam-type phenolic resin. In: Kawai S (ed) Development of ultra-light fiberboard. Report of the Grant-in-Aid for Scientific Research (No. 06660214) from the Ministry of Education, Science and Culture of Japan. Kyoto University, Kyoto, p. 7–15 (In Japanese) (1996).
22) K. Kimoto, E. Ishimori, H. Sasaki and T. Maku: Studies on the particle boards. Report 6: Effects of resin content and particle dimension on the physical and mechanical properties of low-density particle boards. *Wood Research,* **32**, 1–14 (1964).
23) Y. Dong, T. Nakao, C. Tanaka, A. Takahashi and Y. Nishino: Evaluation of the characteristics of wood based panels by the in- and out of- planes vibration technique. *Mokuzai Gakkaishi* **38**(7), 678–686 (in Japanese) (1992).
24) R.F.S. Hearmon: The influence of shear and rotatory inertia on the free flexural vibration of wooden beams. *British. J. of Appl. Phys.,* **9**, 381–388 (1958).
25) R. Nakado: Wood Engineering. Youkendou, p. 215, 396 (In Japanese) (1985).